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On the Thermal Emissivity of a Green Leaf in Still and Moving Air.

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During the recent investigation of the energetics of a foliage leaf,* it was necessary to acquire some knowledge of the rate of interchange of heat between the leaf-lamina and its surroundings for a known excess of temperature, and under given conditions as regards the movement of the surrounding air. It was required, in fact, to determine with some approach to accuracy, the *thermal emissivity in air in absolute units,* including in this term the loss of heat due both to radiation and the conductive and convective properties of the surrounding air. The thermal emissivity is an important factor in the economy of the living plant, since it determines both the maximum temperature to which the leaf can be raised above its surroundings in those cases where the incident radiation is more than sufficient to perform the internal work of the leaf, and also the extent to which the leaf can be cooled below its surroundings when the receipt of radiant energy falls short of that required to produce the observed internal work.

There are comparatively few determinations in absolute units of the thermal emissivity of bodies cooling in air, and the results of experiments such as those of McFarlane on the cooling of a copper ball, or those of J. T. Bottomley, Schleiermacher, and Ayrton and Kilgour on the emissivity of platinum wires, cannot be rendered applicable to our requirements, owing in the first place to the nature of the emitting substances differing so widely from that of a leaf-lamina, and secondly to the fact, emphasized by the experiments of Ayrton and Kilgour,† that the loss of heat from radiation and air convection per square centimetre of surface per one degree excess of temperature is by no means constant, even for substances of a similar nature, and varies greatly with the size and shape of the cooling body.

In the absence of data from which we could deduce even the order of magnitude of the thermal emissivity of a leaf-lamina, it became necessary to attack the problem experimentally, and since the ordinary methods employed for determining the "rate of cooling" of a heated body are manifestly

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* See Brown and Escombe, 'Roy. Soc. Proc.,' this vol., p. 29.

† Phil. Trans.,' A, vol. 183, 1893, p. 371.

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inapplicable to this particular case, we devised an indirect method which has given very good results, and is capable, we believe, of still further extension and refinement. It is based on the following principles:—

A leaf which is actively transpiring tends, by a process of self-cooling, to become lower in temperature than its surroundings. Assuming such a leaf to be placed in an enclosure, the walls and air of which are kept at constant temperature, whilst the air is maintained at a uniform state of humidity, the temperature of the leaf falls to a definite point below that of its surroundings, and then becomes stationary, providing the openings of the stomates do not alter. When this steady thermal condition is reached, the internal work of vaporisation manifestly becomes a measure of the amount of energy flowing into the leaf from its surroundings, providing we neglect, as we may safely do, the very small amount of heat self-produced in the leaf by the respiratory process.*

If, now, we have the means of determining, (1) the amount of water lost by the leaf in a given time by vaporisation; (2) the area of the leaf surface, and (3) the exact difference of temperature between the leaf-lamina and its surroundings, we have all the data necessary for ascertaining the amount of energy in water-gramme-units (calories) which flows into the leaf per unit-area of surface and unit-time for a 1° excess of temperature in the surroundings. But this is the same thing as the *thermal emissivity*, since emission and absorption are equal under the same relative conditions.

The range of temperature of any experiments of this nature is of course small, and it was therefore necessary to devise a form of apparatus, by means of which the temperature difference between the leaf and its environment could be accurately determined.

The thermometric apparatus used consisted of two differential platinum-resistance-thermometers, constructed for us by the Cambridge Instrument Co., and we must here express our great indebtedness to Professor Callendar for his help in designing the apparatus, and for most valuable assistance in other directions during the course of the investigation. The arrangement may be briefly described as follows:—

Two exactly similar frames of very thin ebonite, which in this particular instance had outside dimensions of 11·9 × 11·3 cm. and a width of 0·7 cm., were screwed tightly together on either side of a thin frame of mica which projected a few millimetres into the open part of the ebonite frame. This inner fringing edge of mica-plate was pierced top and bottom with a row of fine holes, through which was threaded a platinum wire of 0·006-inch gauge,

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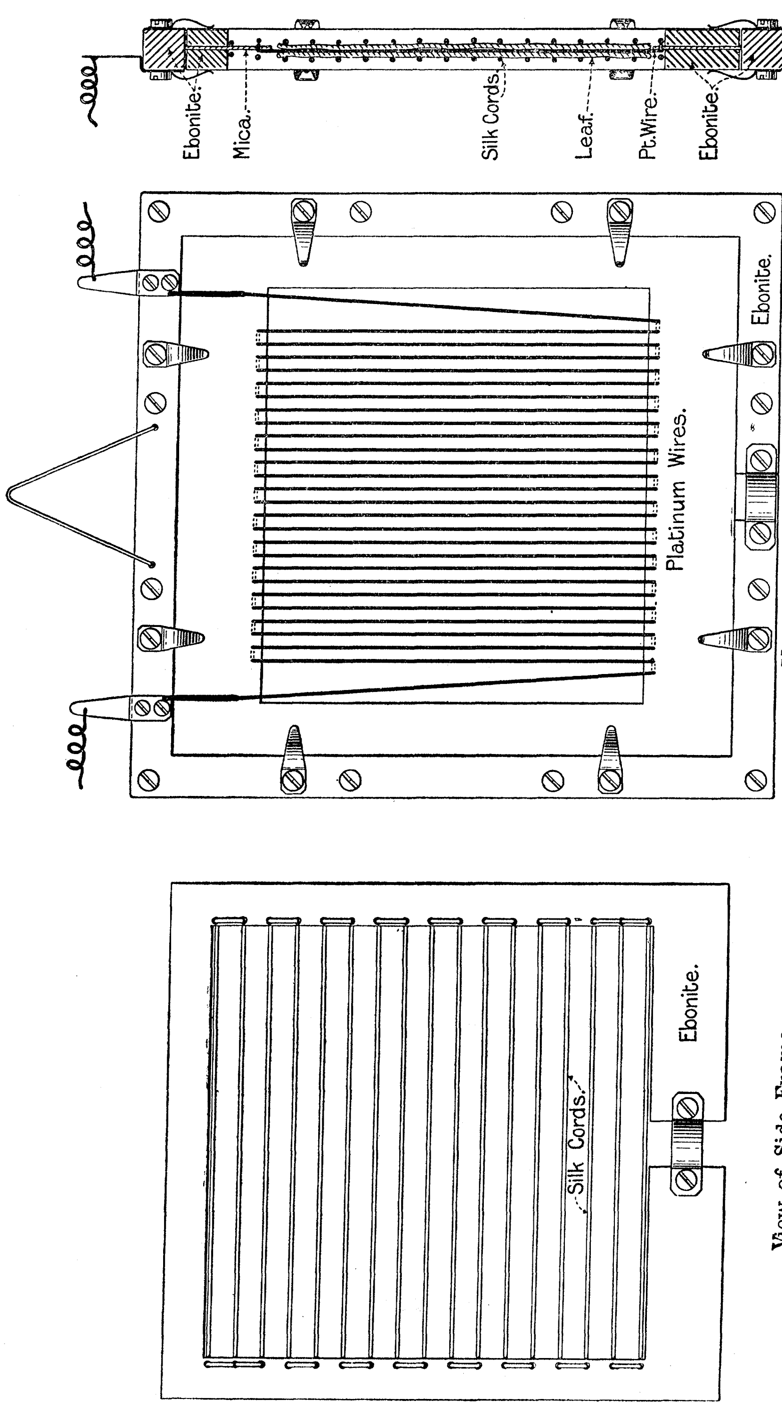
* *Cf.* Brown and Escombe, 'Roy. Soc. Proc.,' this vol., p. 71.



Section.

View with Side Frame removed.

View of Side Frame.

Fig. 1.—Platinum Resistance Thermometer used for Determining Temperature of Leaves.

and of a length of about 2·4 metres, so arranged as to form a flat grid for the leaf-lamina to rest upon. The ends of the platinum coil were attached to two small brass lugs screwed on to the outer ebonite frame, and these could be connected with the leads of the recording instrument by suitable means.

Two other small movable frames of ebonite were constructed, which fitted accurately into either side of the outer frame, and rested, when in position, on the projecting edges of the mica-plate. Across these inner frames were laced thin silk threads for the purpose of lightly pressing the leaf-lamina against the platinum coil.

In using this instrument two similar leaves were always used, these being cut to the proper dimensions for placing in the outer frame. When the inner frames were brought into position, and fixed by means of small brass buttons attached to the outer frame, the platinum-resistance-coil was enclosed by the two leaf-laminæ in close apposition, and was very favourably placed for rapidly acquiring the mean temperature of the leaves.

Since the leaves had to be freely supplied with water, provision had to be made for their petioles to dip into small tubes of water, and for this purpose a portion of the lower part of each of the ebonite frames was cut away and bridged over with a thin curved piece of sheet brass of suitable dimensions. The leaf-stalks passed through a split cork which closed the mouth of the small water-tubes, and this was made tight with a mixture of paraffin and vaseline.* It will be noticed that the leaf surface exposed in this apparatus is always the same. The area of the free space of the inner frame was, in this particular case, 69·72 sq. cm., so that the total leaf surface exposed was 139·44 sq. cm.

The upper part of the outer frame was furnished with a loop of wire, by which the apparatus could be suspended to the arm of the balance when it had to be weighed.

Two exactly similar sets of frames were constructed, each of which, when mounted with their leaves and water-tubes, weighed about 60 grammes.

The difference in temperature between the two coils was determined by means of the Callendar recorder, and the resistance of the coils, which amounted to about 13·8 ohms at 18°·5 C., was very accurately adjusted for a "fundamental interval" of 5 ohms between 0° C. and 100° C., so that when a No. $\frac{1}{2}$ bridge wire was used in the recorder, each scale division of 4 mm.

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* After the cork around the petiole has thus been rendered impervious by the wax, care has to taken to pierce this with a fine needle in order to allow the equalisation of pressure between the outer air and the air of the tube. If this precaution is not taken there is some danger of the free ascent of the water being impeded.

on the revolving drum was equivalent to a temperature difference between the coils of 0°·2 C.; differences of 0°·02 were readily measurable.

Our experiments were originally planned with the idea of determining the temperature-difference between the transpiring leaves and their environment by a comparison of the resistances of the platinum coils when one was clothed with its leaves and the other was exposed to free air. We have, however, to consider the possible effect produced by the heating of the coils during the passage of the current through them.

Mr. Francis Darwin, in a recent paper which came under our notice at the time we were planning these experiments,* has described the application of the platinum-resistance-thermometer and the Callendar recorder to a study of the leaf-temperature as an index of the condition of the stomata. With the small platinum coils he employed, which were wound on plates of talc 10 × 3 mm., it was found that the current used raised the temperature of the coils about 2° above the surrounding air, and that in order to avoid the difficulties introduced by inequalities in the rate of cooling, the central coil had to be covered with a "body equalling in volume and conductivity that on the experimental bulb."

In order to avoid as far as possible in our experiments the complications due to heating of the coils special precautions were taken in their construction, but the heating effect was still a sensible factor when using a current of 0·155 ampères. With a coil resistance of 13·8 ohms the heating effect of the above-mentioned current in each coil was $\frac{(\frac{10}{24}\mathrm{C})^2\mathrm{R}}{\mathrm{J}}$, *i.e.*, 0·01374 calorie per second, or 0·824 calorie per minute. The total surface area of a wire of 0·006-inch gauge and 2·4 metres in length is 11·491 sq. cm., so that the heat produced per square centimetre of surface per second is

$$\frac{0{\cdot}01374}{11{\cdot}491} = 0{\cdot}001195 \text{ calorie.}$$

From the experiments of Ayrton and Kilgour on the thermal emissivity of bright platinum wires of 0·006-inch diameter, we know that at 20° C. the emissivity is about 0·00222 calorie per square centimetre per second for a 1° excess of temperature.† Hence the maximum temperature to which the bare coil will be heated in "still air" by the above-mentioned current is $\frac{0{\cdot}001195}{0{\cdot}00222} = 0^\circ{\cdot}53$ C.‡

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* 'Botanical Gazette,' vol. 37, 1904, p. 81.

† 'Phil. Trans.,' A, vol. 183, 1893, p. 371.

‡ Experimentally the temperature in still air was found to be 0°·54.

If we now suppose the other coil to be clothed with its leaves, the general effect of the heat produced by the current will be to reduce slightly the cooling effect due to transpiration, so that when the steady thermal condition is attained the leaf temperature will be somewhat higher than when no current is passing. If the rise of temperature of this whole system when the static point is reached is exactly equal to the rise of temperature of the bare coil, then the *temperature difference*, which is all that concerns us, will be the same as when no current is passing; in other words, we shall still have a measure of the differential temperature of the leaf and the surrounding air independent of the heating effect of the current.*

The whole question turns on the *thermal emissivity* of the leaf surfaces, which was shown by subsequent experiments to be about 0·00020 calorie per square centimetre of surface per second for a 1° temperature excess.

The total area of leaf surface exposed around the coil is 139·4 sq. cm., and the heat produced in the coil is, as we have seen, 0·01374 calorie per second; hence *when the steady thermal condition is reached*, the temperature of the system will be raised $\frac{0{\cdot}01374}{0{\cdot}0002 \times 139{\cdot}4} = 0^{\circ}{\cdot}49$.

This is only 0°·04 less than the temperature of the uncovered coil when it is in thermal equilibrium with its surroundings, so that the error introduced in determining the temperature difference between a transpiring leaf and its surroundings by comparison with a bare coil such as we used is small when the temperature difference measured amounts, as it frequently does, to 1° or 1°·5 C.

The method, in fact, works very well under perfectly still air conditions, and when precautions are taken to maintain the temperature of the enclosure perfectly constant; but very slight draughts of air or small sudden variations in the temperature of the air necessarily affect the bare coil much more readily than the leaf-covered coil, with the result (one to which Mr. Francis Darwin has already called attention) that the drum-record becomes very unsteady. In order to meet this difficulty we have adopted a modification of the method which is free from these objections, and which is entirely independent both of any heating of the leaf by the current used, and of the small amount of self-heating due to the respiratory process.

If the coils are covered each with a pair of similar leaves of exactly the same area, which differ only in their power of transpiration, and both pairs are placed in the same enclosure under exactly similar conditions as regards temperature and degree of movement of the air, then the difference in the amount of water transpired in a given time as determined by the balance will, when multiplied by the heat of vaporisation, give a measure of the excess number of calories entering the cooler leaf for a temperature gradient equal to the temperature difference given by the integrated record of the drum during the time occupied by the experiment.

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* This argument is not in any way vitiated even if we suppose a portion of the heat of the leaf-clothed coil to be used in promoting increased transpiration.

In order to produce the differential transpiration on which the success of such experiments depends, advantage is taken of the fact that the stomata, through which the greater part of the vaporisation of the water takes place, are very seldom equally distributed on the two sides of the leaf. It is only necessary, therefore, to arrange one pair of leaves with their dorsal sides turned towards the platinum coils, and the other pair with their dorsal sides facing outwards. Hypostomatous leaves lend themselves best to such experiments, providing they are by nature good transpirers, since the dorsal side with its imperforate cuticle loses relatively little water compared with the ventral side.

Any changes in the dimensions of the stomata during an experiment have no influence on the final result, owing to the comparatively rapid thermal adjustments which take place in the leaf. Mr. Francis Darwin has already recorded the fact* which our experiments fully verify, that a slow and gradual closure of the stomata takes place when a cut leaf is placed in darkness. As the stomata close the record of differential temperature on the drum of the recorder approaches more closely the zero line of no temperature difference, but it is the *mean* value with which we alone have to deal in these experiments and, providing the record is correctly integrated, this mean temperature difference and the loss in weight of the two pairs of leaves respectively are the only experimental data required for determining the thermal emissivity of the leaf surface in absolute units.†

As an example of such an experiment performed under "still air" conditions, we may give the following. The leaf cases were placed in a covered tin case which was enclosed in an outer wooden case. A tray containing calcium chloride was placed at the bottom of the tin case in order to keep the air sufficiently dry to promote transpiration.

Experiment on the (hypostomatous) leaves of *Liriodendron tulipifera*.

Temperature of air in the enclosure 18°·6 C.

No. 1 *Coil.*—Leaves arranged with stomatiferous surfaces outwards.

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* *Loc. cit.*

† Before each set of experiments it is always necessary to verify the zero line on the recording drum, since this is at times subject to small variations which are difficult to explain.

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No. 2 *Coil.*—Leaves arranged with stomatiferous surfaces inwards.

Duration of experiment 2 h. 9 m. = 129 minutes.

Area of leaf surface exposed = 139·4 sq. cm.

Water lost by transpiration during experiment:—

No 1	0·640	gramme
„ 2	0·130	„
Difference	0·510	„

The mean temperature difference betwen the two pairs of leaves as indicated by the integration of the drum record was 7·05 scale divisions = 1°·41 C.

Since the difference in the amount of water vaporised by the two pairs of leaves is 0·510 gramme and the latent heat of vaporisation of water at 18°·6 C. is 593·6 water-gramme-units (calories), it follows that 0·510 × 593·6 = 302·7, represents in calories the excess of energy which must have entered the cooler pair of leaves from their surroundings during the experiment, an excess, which is conditioned solely by the temperature gradient of 1°·41 represented by the temperature difference between the two sets of leaves, for all other conditions are similar.

Since the surface area of the exposed leaves in each case is 139·4 sq. cm., and the time occupied by the experiment is 129 minutes, the *thermal emissivity* of this particular kind of leaf expressed in calories per square centimetre of surface per minute, per 1° C. temperature excess, is represented by

$$\frac{302 \cdot 7}{129 \times 139 \cdot 4 \times 1 \cdot 41} = 0 \cdot 01194 \text{ calorie,}$$

or 0·000199 calorie per second.*

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* We have assumed that the thermal emissivity of the upper and lower surface of the leaf-lamina is identical.

Strictly speaking it is the *mean thermal emissivity* of the upper and lower surfaces which is measured by this method, but these mean results can be applied to the determinations of the emissivity of the entire leaf, including both sides, just as well as if we knew the respective emissivities of the two surfaces separately, since it is immaterial whether we take the total emissivity of the leaf as twice the mean value for the two sides, or as the sum of the separate emissivity-values, if these are known.

It is highly probable that even in glabrous leaves the emissivities of the upper and lower surfaces are not quite identical, for "surface emissivity" must depend to some extent on the *heat-conductivity* of the underlying tissue, even in a very thin lamina such as that of an ordinary foliage leaf. One would consequently expect that heat would flow into and out of the leaf somewhat more readily through the cuticle and epidermis overlying the more closely-packed palisade-parenchyma of the dorsal side, than through those portions overlying the spongy parenchyma of the ventral side with its numerous air-spaces.

We propose at some future time to investigate this question, which can be solved in the following manner: Having determined the thermal emissivity of two pairs of leaves, one of

The application of this method has been found to give very concordant results, and although the values have not, perhaps, the degree of precision required in the determination of physical constants, they are sufficiently close approximations to the true values to be exceedingly useful in any investigation of the energetics of the leaf.

It is scarcely to be expected that the thermal emissivities, even of individual leaves of the same plant, should be absolutely identical, and still more might we expect variations in leaves of dissimilar plants. Further investigation can alone decide the magnitude of these variations, but from the results we have obtained with the leaves of the four different species of plants mentioned below it is probable that leaves which are not highly glabrous, to which we have confined our attention, do not vary greatly in "emissivity."

Thermal Emissivity of Leaves of various Species of Plants under "Still Air" Conditions.

Species of Plant.	Thermal emissivity in calories per square centimetre of surface for a 1° C. temperature excess.	
	Per minute.	Per second.
Liriodendron tulipifera (1)	0·01194	0·000199
" " (2)	0·01274	0·000212
Helianthus multiflorus	0·01499	0·000249
Tropœoleum majus	0·01427	0·000237
Tilia europœa	0·01598	0·000266

These emissivities were all determined within a range of temperature of from 17° to 19° C. The variation of the coefficient of emissivity with the temperature can safely be neglected for any range of temperature to which the leaf may be subjected under natural conditions.

It is worthy of note, in passing, that in their order of magnitude, the above values correspond to the emission of heat by a blackened copper sphere 2 cm. in diameter, cooling in air, as determined by McFarlane.* With a 5° temperature difference between the copper ball and its surroundings, he

which is arranged with the dorsal and the other with the ventral sides outwards, the experiment can be repeated after re-arranging the leaves on one coil so that one dorsal and one ventral side is exposed. From the difference, if any, in the emission-values so obtained it will be possible to ascertain the absolute emissivities of the upper and lower sides of the leaf respectively.

* 'Roy. Soc. Proc.,' vol. 20, 1871, p. 90.

found that the heat emitted per second, per 1° difference of temperature, per square centimetre of surface, was 0·000252 calorie.

The Thermal Emissivity of a Leaf in Moving Air.

In the experiments so far recorded, we have confined our attention to the "rate of cooling" of a leaf under "still air" conditions, that is to say, under conditions in which the leaf was shielded from direct draughts, and, as regards mass-movement of the air, was only subjected to the slight convective currents induced by the temperature differences between the leaves and their environment.

We have still to consider the influence of comparatively rapid air-currents of determinate velocity on the rate of transference of energy to and from the leaf, a matter of considerable importance in any study of the energetics of the leaf, especially as regards the dissipation of the excess of incident solar energy under open air conditions.

It has already been pointed out elsewhere* that, owing to the structure of the leaf, the rapidity of the transpiratory process, under fixed conditions of temperature and air-humidity, will not be much influenced by merely increasing the velocity of the air passing over the surface of the leaf when once a very moderate degree of velocity is exceeded. If, therefore, we have two pairs of leaves placed in the thermometric apparatus already described, and we arrange them so as to produce differential transpiration, the general tendency of a steady current of air passing over the leaves will be to diminish the temperature difference which they exhibit in still air conditions. Hence by extending our observations to leaves placed in air-currents of known velocity, we can determine the increase in the thermal emissivity due to this cause.

Before proceeding to describe our experiments in this direction we must refer to a previous paper which has a direct bearing on the subject.

So far as we know the only experiments which have been made on the influence of air-currents of definite velocity on the rate of cooling of a heated body are those of Crichton-Mitchell.† The author employed a blackened copper sphere which had a diameter of 2 inches, and the rate of cooling was determined in steady air-currents of determinate velocity. It was found that within limits of 200° C. temperature excess and a speed of air-current of 1000 metres per minute Newton's, "Law of Cooling" is accurate, provided the speed of the air-current passing the surface of the cooling body be sufficient.

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* Brown and Escombe, 'Roy. Soc. Proc.,' this vol., p. 79.

† 'Roy. Soc. Edin. Trans.,' vol. 40, 1900, p. 39.

Moreover, and this is the point which is of particular interest for us, the cooling influence of the air is *directly proportional to its speed* up to velocities of about 300 metres per minute (18 kilometres per hour). Beyond this velocity of 300 metres the cooling influence in the case of the copper ball fell off somewhat. The explanation given, which is no doubt the correct one, is that when a body is cooling in air, the effect of radiation, which involves higher powers of the temperature excess (Stefan's " fourth-power law ") is small compared with the effect produced by convection.*

Crichton-Mitchell's results are not expressed in absolute units, but from the data given it is possible to make a fairly close approximation to these. With a temperature difference of 10° C. between the copper ball and the air (the lowest experimental difference recorded) we have calculated (approximately) the calories lost per square centimetre of surface per minute for a 1° temperature excess for each of the given velocities of the air-current from 41 to 976 metres per minute. When the results were plotted the cooling effect of the air-current was seen to be practically a linear function of the speed up to velocities of 300 metres per minute, and that the extra cooling effect induced by the air-current amounted to 0·000206 calorie per square centimetre per minute per 1° C. excess, for an increased speed of the current of 1 metre per minute. But here again we are prevented from applying these values with any degree of certainty to the rate of cooling of a leaf owing to the different nature and shape of the cooling bodies. In the paper just cited the author proposed to apply his method of investigation to the cooling in moving air of a strip of platinum foil heated by means of an electric current, and it is probable that owing to the closer similarity in the shape of a platinum strip to the leaf-lamina such an experiment might give results which would have a more direct bearing on the special case we are considering, although there would still be the uncertainty due to the very different nature of the two laminæ.†

Our experiments on the influence of currents of air on the thermal emissivity of foliage leaves were carried out on lines very similar to those of Crichton-Mitchell, but owing to the differential method employed the apparatus admitted of simplification, the use of a water-jacket around the cooling body being unnecessary in our case.

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* How relatively small a part radiation plays in the cooling of a heated body in air is shown by J. T. Bottomley's experiments ('Phil. Trans.,' A, vol. 178, 1887, p. 429) on the emissivity of heated platinum wires. From a series of experiments made in a high vacuum and in air at varying pressures it was found that only about 5 per cent. of the emissivity in air at 740 mm. was due to radiation.

† Professor Crichton-Mitchell has recently laid before the Royal Society of Edinburgh a preliminary account of his experiments on the cooling of a strip of platinum under the above conditions, but at the time of writing these results are not available.

In an aperture in one side of an air-tight box 3 feet cube was fixed an exhaust electric fan, 12 inches in diameter, and driven by an attached motor, which was connected with a speed-regulator under ready control. Into the side of the box opposite the fan opened a horizontal wooden shaft 5 feet in length. For the greater part of its length the cross section of this shaft was 10 inches square, but just before entering the box it was reduced to 5 inches, and at this point there was inserted an aluminium fan-anemometer constructed by Richard Frères. By means of this simple apparatus a steady current of air could be maintained in the horizontal shaft at determinate velocities up to about 140 metres per minute (8·4 kilometres per hour). The thermometric coils carrying the leaves were inserted through a small door in the middle of the shaft. They were placed at a sufficient distance apart to prevent any mutual disturbance, and with their planes parallel to the current of air which passed over the leaf surfaces.

The pairs of leaves covering the coils were arranged for differential transpiration in the manner already described, and a series of experiments was made for determining the thermal emissivity with air-currents of varying speeds on exactly the same lines as those for "still air" conditions.

The following results were obtained with leaves of *Liriodendron tulipifera* :—

Speed of air-current in metres per minute.	Thermal emissivity in calories per square centimetre of leaf surface per 1° C. temperature excess.	
	Per minute.	Per second.
"Still air"	0·0119	0·000198
36·2 metres	0·0173	0·000288
71·4 "	0·0238	0·000396
108 "	0·0304	0·000506
139 "	0·0361	0·000601

These results are plotted out in fig. 2, and clearly show that up to speeds of 140 metres per minute, the increased rate of cooling or heating of a leaf induced by a steadily moving current of air is directly proportional to the speed of the current passing over the surface of the lamina. This is

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quite in accordance with the general results obtained by Crichton-Mitchell, from which we are justified in concluding that the same law would hold good for even higher speeds, *i.e.*, up to at least 300 metres per minute (18 kilometres per hour).

The increase in thermal emissivity for a velocity of 1 metre per minute is seen to be 0·000174 calorie per square centimetre of leaf surface per minute per 1° C. difference of temperature between the leaf and the air.

Another similar experiment with the leaves of *Helianthus multiflorus*, having a thermal emissivity under "still air" conditions of 0·0150 calorie per square centimetre per minute per 1° C. excess temperature, showed an emissivity of 0·0338 calorie in an air-current of a speed of 109·8 metres per minute. This result is also plotted in the accompanying figure, and it will be seen that the line is sensibly parallel to that given by the experiments on *Liriodendron*, the rise of emissivity for an increased speed of 1 metre per minute being 0·000171 calorie, against 0·000174 calorie in the case of the *Liriodendron*. This renders it probable that although there are small initial differences in the emissivity of leaves under "still air" conditions, the influence of moving air-currents on all glabrous and moderately thin leaves in effecting transference of heat from and to the leaf is practically identical.

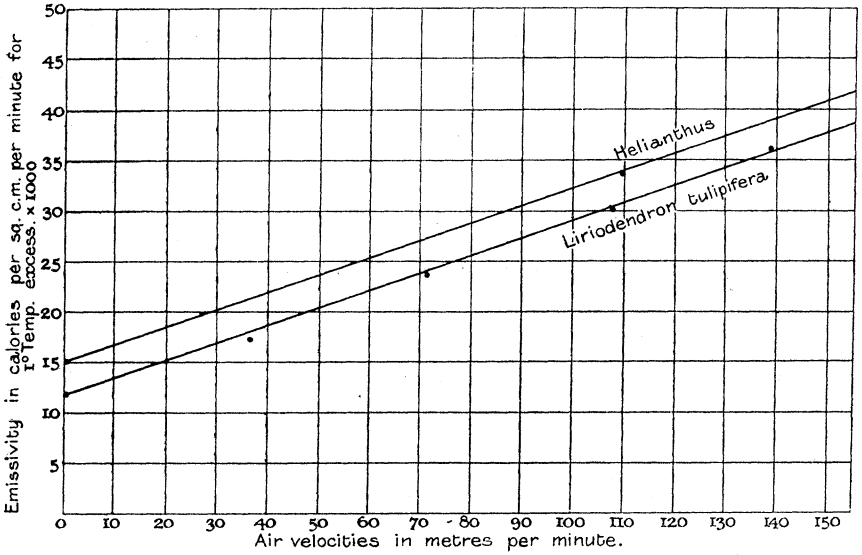

FIG. 2.

From the magnitude of the thermal effects produced by moving air it will be evident that this mode of dissipating the excess of radiant energy falling on the leaf must be of great importance, especially in those cases where the transpiratory work performed is small. Let us consider a somewhat extreme case in which the leaf is receiving solar radiation amounting to 1 calorie per square centimetre per minute, and let us assume that the absorption coefficient of the leaf for this radiation is 0·75, and that the leaf possesses a thermal emissivity equal to that of the *Liriodendron*, *i.e.*, 0·0119 calorie per square centimetre per minute for a temperature excess of 1° C. The total emissivity of the two surfaces of the leaf will, of course, be double this amount, *i.e.*, 0·0238 calorie per square centimetre per minute for a 1° excess.

If we assume transpiration to be entirely in abeyance, the temperature to which the leaf will be raised above the surrounding air when the emission exactly balances the absorbed radiation will be represented by $\frac{0 \cdot 75}{0 \cdot 0238} = 31^\circ \cdot 5$ C., an excess which would speedily prove fatal to the leaf, even supposing the surrounding air to have a temperature as low as 20° C. If, however, we suppose the air to be in gentle movement at the rate of about 8·5 kilometres per hour (141 metres per minute), the emissivity of the leaf, counting both sides, becomes $0 \cdot 0361 \times 2 = 0 \cdot 0722$ calorie per square centimetre per minute for 1° of excess, and the leaf therefore cannot rise in temperature above the surrounding air more than $\frac{0 \cdot 75}{0 \cdot 0722} = 10^\circ \cdot 3$ C., even when there is no dissipation of the absorbed energy by transpiration.

The importance of facts such as these in connection with the life-history of the xerophytic plants is considerable, and we are in a better position to give quantitative expression to these and similar problems connected with the energetics of the plant, now we have the means of determining the thermal emissivity of plant surfaces and the wastage of energy due to this cause.

We have shown above how it is possible to determine the thermal emissivity of a leaf both for "still air" conditions and for any given velocity of an air-current, provided we know the weight of water transpired per unit-area and unit-time, and also the temperature difference involved. Since, however, these three values representing thermal emissivity, water transpired, and temperature difference, are interdependent, it follows that when any two are known the third is calculable. Their relations may be conveniently generalized as follows:—

Let Q represent the amount in grammes of the water transpired per square centimetre of leaf-lamina per minute;

h, the latent heat of vaporisation of water at the temperature of the air* expressed in water-gramme-units;

$(\theta-\theta_n)$ the temperature difference observed; and

e the thermal emissivity of the leaf in calories per square centimetre of leaf surface, per minute, for a 1° C. temperature excess.

Then (1) $e = \frac{Qh}{(\theta-\theta_n)}$, (2) $Q = \frac{e(\theta-\theta_n)}{h}$, (3) $(\theta-\theta_n) = \frac{Qh}{e}$.

Having once established and plotted the values of e for a particular kind of leaf, and for given conditions of air-movement it becomes possible by means of equation (2) to translate the temperature-records of the drum of the recorder, for any period, or for any particular moment of time, into *grammes of water transpired per unit-area, and unit-time.* If we are measuring the difference of temperature between the leaf and the surrounding air, it is the total loss of water by the leaf which is thus measured, whilst on the other hand, if both thermometer-coils are furnished with leaves, it is of course only the *differential transpiration-effect* which is determined.

As an example, we may take an experiment on the differential transpiration of two pairs of leaves of *Liriodendron tulipifera* in moving air, the details of which were as follows:—

Time occupied by the experiment, two hours.
Temperature of the air, 18°·5 C.
Latent heat of vaporisation (h) = 593·7 calories.
Mean differential temperature of the pairs of leaves $(\theta-\theta_n) = 0°\cdot43$ C.
Velocity of air-current 71·4 metres per minute.

The thermal emissivity (e) of this leaf in an air-current of the above velocity is

$$e = 0\cdot0119 + (0\cdot000174 \times 71\cdot4) = 0\cdot0243.$$

From equation (2) the mean differential transpiration per square centimetre of leaf-lamina per minute, will be

$$Q = \frac{0\cdot0243 \times 0\cdot43}{593\cdot7} = 0\cdot0000176 \text{ gramme.}$$

This is equivalent to a differential transpiration of 0·1056 gramme *per square decimetre per hour.*

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* The latent heat of vaporisation is represented by $606\cdot5 - 0\cdot695\ \theta$, where θ is the temperature of the air. Strictly speaking it is the temperature of the transpiring leaf which should be taken to represent θ, or, in the case of differential transpiration, the mean temperature of the two sets of leaves, but the error introduced from this cause is insignificant, amounting to not more than about 0·1 per cent.

The actual difference in the weight of water lost by the two leaf-cases during two hours as determined by the balance was 0·290 gramme, and since the total leaf surface exposed in each case was 139·4 square centimetres, the differential loss *per square decimetre per hour* was $\frac{0{\cdot}290 \times 100}{139{\cdot}4 \times 2} = 0{\cdot}1040$ gramme, against 0·1056 gramme, as determined from the differential temperature of the leaves.

It seems probable that this method of determining the rate of transpiration by a mere observation of temperature differences may be of service to those who are engaged in such investigations, since when once the thermal emissivity of the leaf is known, the position of the pen on the drum of the recorder enables us to determine at any desired moment the actual amount of transpiration which is going on in the leaf.

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